

# Flavour Dynamics – Central Mysteries of the Standard Model <sup>1</sup>

I. I. Bigi

*Physics Dept., Univ. of Notre Dame du Lac, Notre Dame, IN 46556, U.S.A.*

*e-mail address: bigi@undhep.hep.nd.edu*

## Abstract

After pointing out the amazing success of the CKM description in accommodating the phenomenology of flavour changing neutral currents I review the status of theoretical technologies for extracting CKM parameters from data. I sketch novel directions, namely attempts to deal with quark-hadron duality in a (semi)quantitative way and to develop a QCD description of two-body modes of  $B$  mesons. After commenting on predictions for  $\epsilon'/\epsilon$  and CP asymmetries in  $B$  decays I address indirect probes for New Physics in  $D^0$  oscillations and CP violation, in  $K_{\mu 3}$  decays and electric dipole moments. I describe in which way searching for New Physics in  $B$  decays provides an exciting adventure with novel challenges not encountered before.

## Contents

<b>1</b>	<b>New Landmarks and Challenges</b>	<b>2</b>
<b>2</b>	<b>The Charged Current Dynamics of Quarks</b>	<b>3</b>
2.1	The ‘unreasonable’ Success of the CKM Description . . . . .	3
2.2	Extracting CKM Parameters . . . . .	4
2.3	Quark-Hadron Duality – a New Frontier . . . . .	8
2.4	Lifetimes as Validation Studies . . . . .	9
2.5	Exclusive Nonleptonic $B$ Decays – another New Frontier . . . . .	9
2.6	Radiative $B$ Decays . . . . .	10
<b>3</b>	<b>CP Violation in <math>\Delta S, \Delta B \neq 0</math></b>	<b>11</b>

---

<sup>1</sup>Plenary Talk given at ICHEP2000, July 27 - August 2, 2000, Osaka, Japan

<b>4</b>	<b>Probing for New Physics</b>	<b>13</b>
4.1	$D^0$ Oscillations & CP Violation . . . . .	13
4.2	$P_{\perp}(\mu)$ in $K^+ \rightarrow \mu^+ \pi^0 \nu$ . . . . .	14
4.3	EDM's . . . . .	15
4.4	KM Trigonometry . . . . .	15
4.5	On Theoretical Uncertainties . . . . .	16
4.6	Looking into the Crystal Ball . . . . .	17
<b>5</b>	<b>Conclusions &amp; Outlook</b>	<b>17</b>

Flavour dynamics involve central mysteries of the Standard Model (SM): Why is there a family structure relating quarks and leptons? Why is there more than one family, why three, is three a fundamental parameter? What is the origin of the observed pattern in the quark masses and the CKM parameters?

There are two different strategies for obtaining answers to these questions:

(A) One argues that one has already enough data and therefore can turn one's energy towards the last fundamental challenge, namely to bring gravity into the quantum world; flavour dynamics with its family structure will then emerge as a 'side product'.

(B) Suspecting that nature has a few more surprises up her sleeves one commits oneself to elicit more answers from her.

My talk is geared towards strategy (B) and its necessary theoretical tools. I will list experimental numbers without going into details; those can be found in Golutvin's talk [1].

## 1 New Landmarks and Challenges

Since ICHEP98 new landmarks have been reached:

- *Direct* CP violation has been established experimentally – a discovery of the first rank irrespective of theoretical interpretations.
- We are on the brink of observing CP violation in  $B$  decays.
- We are reaching fertile ground for finding New Physics in  $D^0$  oscillations and CP violation.

On the theory side we are learning lessons of humility, increasing the sophistication of our theoretical technologies, and pushing back new frontiers.

All of this leads to new challenges for theory, namely to regain theoretical control over  $\epsilon'/\epsilon$ ; to develop reliable quantitative predictions for CP asymmetries in  $B$  decays and to refine them into precise ones; to establish theoretical control over  $D^0$

oscillations and CP violation and finally, to develop comprehensive strategies to not only establish the intervention of New Physics, but also identify its salient features.

A major part of my talk will address extracting numerical values of CKM parameters; I will discuss possible limitations to quark-hadron duality and refer to the lifetimes of charm and beauty hadrons as validation studies before describing new attempts to describe exclusive nonleptonic  $B$  decays; I will sketch the difficulties inherent in predicting  $\epsilon'/\epsilon$  before addressing CP violation in  $B$  decays; I will comment on future searches for New Physics based on CKM trigonometry and the nature of theoretical uncertainties before describing ‘exotic’ searches for transverse polarization of muons in  $K_{\mu 3}$  decays, electric dipole moments and CP violation in charm transitions.

## 2 The Charged Current Dynamics of Quarks

### 2.1 The ‘unreasonable’ Success of the CKM Description

The observation of the ‘long’  $B$  lifetime of about 1 psec together with the dominance of  $b \rightarrow c$  over  $b \rightarrow u$  revealed a hierarchical structure in the KM matrix that is expressed in the Wolfenstein representation in powers of  $\lambda = \text{tg}\theta_C$ . We often see plots of the CKM unitarity triangle where the constraints coming from various observables appear as broad bands [2]. While the latter is often bemoaned, it obscures a more fundamental point: the fact that these constraints can be represented in such plots at all is quite amazing! Let me illustrate that by an analogy first: plotting the daily locations of the about 1000 high energy physicists attending this meeting on a city map of Osaka produces fairly broad bands. Yet the remarkable thing is that these 1000 people are in Osaka rather than spread over the world. On a map of Japan (let alone the world) these bands shrink to a point showing that the whereabouts of these physicists follow an a priori highly unlikely distribution for which there must be a good reason. Likewise one should look at the bigger picture of flavour dynamics. The quark box *without* GIM subtraction yields a value for  $\Delta m_K$  exceeding the experimental number by more than a factor of thousand; it is the GIM mechanism that brings it down to within a factor of two or so of experiment. The GIM subtracted quark box for  $\Delta M_B$  coincides with the data again within a factor of two. Yet if the beauty lifetime were of order  $10^{-14}$  sec while  $m_t \sim 180$  GeV it would exceed it by an order of magnitude; on the other hand it would undershoot by an order of magnitude if  $m_t \sim 40$  GeV were used with  $\tau(B) \sim 10^{-12}$  sec; i.e., the observed value can be accommodated because a tiny value of  $|V(td)V(ts)|$  is offset by a large  $m_t$ .

This amazing success is repeated with  $\epsilon$ . Over the last 25 years it could always be accommodated (apart from some very short periods of grumbling mostly off the record) whether the *correct* set [ $m_t = 180$  GeV with  $|V(td)| \sim \lambda^3$ ,  $|V(ts)| \sim \lambda^2$ ] or the *wrong* one [ $m_t = 40$  GeV with  $|V(td)| \sim \lambda^2$ ,  $|V(ts)| = \lambda$ ] were used. Yet both  $m_t = 180$  GeV with  $|V(td)| = \lambda^2$ ,  $|V(ts)| = \lambda$  as well as  $m_t = 40$  GeV with

$|V(td)| = \lambda^3$ ,  $|V(ts)| = \lambda^2$  would have lead to a clear inconsistency!

Thus the phenomenological success of the CKM description has to be seen as highly nontrivial or ‘unreasonable’. This cannot have come about by accident – there must be a good reason.

## 2.2 Extracting CKM Parameters

A crucial element in extracting CKM parameters defined for the quark degrees of freedom from data involving hadrons is the quality of our theoretical technologies to deal with the strong forces. For strange mesons with  $m_s < \Lambda_{QCD}$  one invokes chiral perturbation theory, for beauty hadrons with  $m_b \gg \Lambda_{QCD}$  the heavy quark expansion (HQE) which might be extended to charm hadrons in a semiquantitative fashion ( $m_c > \Lambda_{QCD}$ )<sup>2</sup>. Lattice QCD on the other hand deals with the nonperturbative dynamics of all quark flavours.

Both HQE and lattice QCD (to be discussed in Kenway’s lecture [3]) represent mature technologies with large common ground (both operate in Euklidian space) that are complementary to each other. There has already been fruitful feedback between the two on the conceptual as well as numerical level; this interaction is about to intensify. While quark models no longer represent state-of-the-art, they still serve useful purposes in the diagnostics of our results if employed properly.

The main tool for numerical results so far have been the HQE. The last few years have seen a conceptual convergence among its practitioners: most of them accept the argument that HQE allow to describe in principle nonleptonic as well as semileptonic beauty decays as long as an operator product expansion can be relied upon. At the same time one fully expects the numerical accuracy to decrease when going from  $B \rightarrow l\nu q\bar{q}'$  to  $B \rightarrow c\bar{u}d\bar{q}'$  and on to  $B \rightarrow c\bar{c}s\bar{q}'$  for fundamental as well practical reasons (the latter meaning that the energy release is lowest for  $b \rightarrow c\bar{c}s$ ). Considerable progress has been achieved also in the numerical value of basic quantities the most important one being the beauty quark mass. Last year three groups extending earlier work by Voloshin [5] have presented new extractions from data, which – when expressed in terms of the so-called ‘kinetic’ mass – read as follows:

$$m_b^{\text{kin}}(1 \text{ GeV}) = 4.56 \pm 0.06 \text{ GeV} [6], 4.57 \pm 0.04 \text{ GeV} [7], 4.59 \pm 0.06 \text{ GeV} [8] \quad (1)$$

The error estimates of 1 - 1.5 % might be overly optimistic (as it often happens), but not foolish. Since all three analyses use basically the same input from the  $\Upsilon(4S)$  region, they could suffer from a common systematic uncertainty, though. This can be checked by analysing the shape of the lepton spectrum in  $B \rightarrow l\nu X$ . More concretely one forms two moments both of the lepton and of the hadron energies [9]; each set yields  $\bar{\Lambda}$  and  $\mu_\pi^2$ , where  $\bar{\Lambda} \rightarrow M_B - m_b$  as  $m_b \rightarrow \infty$  and  $\mu_\pi^2 \equiv \langle B|\bar{b}(iD)^2 b|B\rangle/2M_B$ .

---

<sup>2</sup>The situation is qualitatively different for top states: with  $\Gamma_t \sim \mathcal{O}(\Lambda_{QCD})$  top quarks decay before they can hadronize and they are therefore controlled by perturbative QCD [4].

Comparing those two sets of values with each other and with the  $m_b$  values listed above represents a crucial self-consistency check. An early CLEO analysis appeared to yield inconsistent values. It is being redone now, and I eagerly await their results; yet I do that with considerable confidence, in particular since a recent lattice study [10] has yielded numbers that are in agreement with those inferred from the SV sum rules [11].

Two methods exist with excellent theoretical credentials for determining  $V(cb)$ :

(i) Extrapolating the rate of  $B \rightarrow l\nu D^*$  to zero recoil one extracts  $V(cb)F_{D^*}(0)$ . The form factor  $F_{D^*}(0)$  has the nice features that it is normalized to unity in the infinite mass limit and that the leading nonperturbative correction is of order  $1/m_Q^2$ . Unfortunately it is  $m_c$  that sets the scale here rather than  $m_b$ , and that is one of the challenges in evaluating it. Three estimates provide representative numbers:

$$F_{D^*}(0) = 0.89 \pm 0.08 \text{ [13]}, \quad 0.913 \pm 0.042 \text{ [14]}, \quad 0.935 \pm 0.03 \text{ [15]} \quad (2)$$

I will use here

$$F_{D^*}(0) = 0.90 \pm 0.05 \quad (3)$$

as a convenient *reference* point. CLEO has presented a new analysis that yields a considerably larger number than before [16]:

$$|V(cb)F_{D^*}(0)| = (42.4 \pm 1.8|_{stat} \pm 1.9|_{syst}) \times 10^{-3} \quad (4)$$

The updated LEP number on the other hand has hardly changed [17]:

$$|V(cb)F_{D^*}(0)| = (34.9 \pm 0.7|_{stat} \pm 1.6|_{syst}) \times 10^{-3} \quad (5)$$

There is now about a 20% difference between the two central values, which means that ‘stuff happens’. With Eq.(3) one gets:

$$|V(cb)|_{excl,CLEO} = (47.1 \pm 2.0|_{stat} \pm 2.1|_{syst} \pm 2.1|_{th}) \times 10^{-3} \quad (6)$$

$$|V(cb)|_{excl,LEP} = (38.8 \pm 0.8|_{stat} \pm 1.8|_{syst} \pm 1.7|_{th}) \times 10^{-3} \quad (7)$$

I view a theoretical error of 5% as on the optimistic side, and I am skeptical about being able to reduce it below this level.

(ii) The *inclusive* semileptonic width of  $B$  mesons can be calculated in the HQE:  $\Gamma_{SL}(B) \propto m_b^5 \cdot (1 + \mathcal{O}(1/m_b^2) + \mathcal{O}(\alpha_S))$ . Again there is no correction  $\sim \mathcal{O}(1/m_Q)$ . The advantage over the previous case is that the expansion parameter is effectively the inverse energy release  $\sim (m_b - m_c)^{-1}$  rather than the larger  $1/m_c$ ; the challenge is provided by the fact that the leading term depends on the fifth power of the  $b$  quark mass. It was only the great conceptual and technical progress in HQE that made this method competitive.

LEP has updated its analysis and finds:

$$|V(cb)|_{incl} = (40.76 \pm 0.41|_{stat} \pm 2.0|_{th}) \times 10^{-3} \quad (8)$$

The theoretical error has been evaluated in a fairly careful way [12]; I am quite optimistic that it can be cut in half in the foreseeable future; but even then it would appear to represent the limiting factor. Yet it is mandatory to check the small overall experimental error. CLEO has amassed a huge amount of data on tape; I am most eager to see their findings.

The first *direct* evidence for  $V(ub) \neq 0$  came from the endpoint spectrum in *inclusive* semileptonic  $B$  decays. Such studies yielded  $|V(ub)|_{end} = (3.2 \pm 0.8) \times 10^{-3}$  with a heavy reliance on theoretical models which makes both the central value and the error estimate suspect. Yet with huge new data sets becoming available, this avenue should be re-visited due to the following two observations:

- The  $AC^2M^2$  model constitutes a good implementation of QCD, in particular for  $b \rightarrow u$  transitions [18]. The main caveat is that one should not determine the two model parameters  $p_F$  and  $m_{sp}$  from the  $b \rightarrow c$  spectrum and then apply it blindly to  $b \rightarrow u$  decays. With sufficient statistics one can fit it directly to the  $b \rightarrow u$  spectrum even over the very limited kinematical regime where it can be cleanly separated from  $b \rightarrow c$ .
- A few years ago it has been suggested [43] to extract the required shape function for  $b \rightarrow u$  from the measured photon spectrum in  $B \rightarrow \gamma X$ . This might become a feasible procedure with future data. Some more theoretical work is needed, though, a point I will return to.

From the exclusive channels  $B \rightarrow l\nu\pi$  and  $B \rightarrow l\nu\rho$  one has inferred

$$|V(ub)|_{excl} = (3.25 \pm 0.14|_{stat.} \pm 0.27|_{syst.} \pm 0.55|_{th}) \times 10^{-3} \quad (9)$$

There is a very strong model dependance, and it is quite unclear to me whether the theoretical uncertainty has been evaluated in a reliable fashion by comparing the findings from various quark models and QCD sum rules. One hopes that lattice QCD will provide the next step forward.

LEP groups have made the heroic effort to extract the total width  $\Gamma(H_b \rightarrow l\nu X_{no\ charm})$ . Their findings read as follows [1]:

$$|V(ub)|_{\Gamma_{SL}} = (4.04 \pm 0.44|_{stat} \pm 0.46|_{b \rightarrow c, syst} \pm 0.25|_{b \rightarrow u, syst} \pm 0.02|_{\tau_b} \pm 0.19|_{HQE}) \times 10^{-3} \quad (10)$$

The theoretical uncertainties in this fully integrated width are under good control [19]; however it is an experimental tour de force, as already indicated by the errors, with the uncertainty in the modelling for  $b \rightarrow c$  the central one.

The main drawback in using the charged lepton energy as a kinematical discriminator is its low efficiency: about 90% of the  $b \rightarrow u$  events are buried under the huge  $b \rightarrow c$  background. The hadronic recoil mass spectrum  $\frac{d}{dM_X}\Gamma(B \rightarrow l\nu X)$  provides a much more efficient filter with only about 10% of  $b \rightarrow u$  being swamped by  $b \rightarrow c$  as first suggested within a parton model description [20]. Using HQE methodology it has been shown that the theoretical description can be based more directly on QCD

[21, 22]. Furthermore the fraction of  $b \rightarrow u$  events below  $M_X \sim 1.6$  GeV appears to be fairly stable. The predicted  $M_X$  spectrum can be compared with data – if one ‘smears’ the latter over energy intervals  $\sim \Lambda$ . Refinements of these ideas are under active theoretical study [23].

(i)  $|V(td)|$  can be inferred from  $B_s$  oscillations <sup>3</sup>

$$\frac{x_d}{x_s} \simeq \frac{|V(td)|^2 B f^2(B_d)}{|V(ts)|^2 B f^2(B_s)}, \quad (11)$$

although even the relative size of  $B_d$  and  $B_s$  oscillations could be affected significantly by New Physics. (ii) Another approach is to compare *exclusive* radiative decays  $B \rightarrow \gamma \rho/\omega$  vs.  $B \rightarrow \gamma K^*$ . Yet one has to keep in mind here that long distance physics could affect  $B \rightarrow \gamma \rho$  much more than  $B \rightarrow \gamma K^*$ . (iii) The cleanest way theoretically is provided by the width for  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ . With the hadronic matrix element inferred from  $\Gamma(K^+ \rightarrow \pi^0 l^+ \nu)$  the contributions from intermediate charm quarks provide the irreducible theoretical uncertainty estimated to be around several percent. With the present loose bounds on  $|V(td)|$  one expects [24]

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.82 \pm 0.32) \cdot 10^{-10} \quad (12)$$

One candidate has been observed by E787 at BNL corresponding to

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.5^{+3.4}_{-1.2}) \cdot 10^{-10} \quad (13)$$

The single event sensitivity is supposed to go down to  $0.7 \cdot 10^{-10}$ ; the successor experiment E949 hopes for a sensitivity of  $\sim 10^{-11}$ .

*In summary:*

- There are two ways for extracting  $|V(cb)|$  from semileptonic  $B$  decays where the *theoretical* uncertainty has been reduced to about 5% with a further reduction appearing feasible. This theoretical confidence cannot be put to the test yet due to a divergence in the available data.
- PDG2K quotes a  $\sim 40$  % error on  $V(ub)$ . The situation will improve qualitatively as well as quantitatively: reducing uncertainties down to the 10% level seems feasible, and in the long run one can dream to go even beyond that!
- Observing  $B_s$  oscillations and  $B \rightarrow \gamma \rho/\omega$  would elevate our knowledge of  $|V(td)|$  to a new level: in particular the former should yield a value with an error not exceeding 10 %, although it could be affected very significantly by New Physics; an intriguing long term prospect is provided by  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ .

---

<sup>3</sup>The 3-family unitarity constraint  $|V(ts)| \simeq |V(cb)|$  is assumed throughout this talk unless stated otherwise.

## 2.3 Quark-Hadron Duality – a New Frontier

When extracting the value of CKM parameters with few percent errors only, one has to be concerned about several sources of *systematic* uncertainties, prominent among them theoretical ones. A fundamental one is the assumption of *quark-hadron duality* (QHDu) that enters at various stages of the theoretical reasoning. When calculating a rate on the quark-gluon level QHDu is invoked to equate the result with what one should get for the corresponding process expressed in hadronic quantities.

QHDu *cannot* be exact: it is an approximation the quality of which is process-dependant – it should work better for semileptonic than nonleptonic transitions – and increases with the amount of averaging or ‘smearing’ over hadronic channels. There is a lot of folklore that leads to several useful concepts – but no theory. That is not surprising: for QHDu can be addressed in a quantitative fashion only *after* nonperturbative effects have been brought under control, and that has happened only relatively recently in beauty decays.

Developing such a theory for QHDu thus represents a new frontier requiring the use of new tools. Considerable insight exists into the physical origins of QHDu violations: (i) They are caused by the exact location of hadronic thresholds that are notoriously hard to evaluate. Such effects are implemented through ‘oscillating terms’; i.e., the fact that innocuous, since suppressed contributions  $\exp(-m_Q/\Lambda)$  in Euclidean space turn into dangerous while unsuppressed  $\sin(m_Q/\Lambda)$  terms in Minkowski space. (ii) There is bound to be some sensitivity to ‘distant cuts’ [11]. (iii) The validity of the  $1/m_c$  expansion arising in the description of  $B \rightarrow l\nu D^*$  is far from guaranteed.

The OPE *per se* is insensitive to QHDu violations (although it provides some indirect qualitative insights). One can probe QHDu in exactly solvable model field theories among which the ’t Hooft model – QCD in 1+1 dimensions with  $N_C \rightarrow \infty$  – has gained significant consideration. It had been suggested [25], based on a numerical analysis, that nonleptonic transitions exhibit significant or even large QHDu violations; yet analytical studies revealed such violations to be tiny only [26], even in spectra [27].

A more convincing probe for QHDu violations would be based on a procedure familiar from experimental analyses: one employs different methods to determine the same basic quantity. I have already listed one example, namely to extract  $m_b$  from  $\Upsilon(4S)$  spectroscopy as well as the leptonic and hadronic moments in  $B$  decays. One very telling implementation of such a program would be to determine CKM parameters in  $B_s$  decays and compare the results with the findings in  $B_{u,d}$  decays. For practical reasons one would probably be limited to compare the leptonic and hadronic moments in semileptonic  $B_s$  decays and to infer  $|V(bc)|$  from  $\Gamma_{SL}(B_s)$  and  $B_s \rightarrow l\nu D_s^*$ . Comparing  $B_s$  with  $B$  results is much more revealing than comparing  $B_d$  with  $B_u$  decays. For a likely source of QHDu violations in  $b \rightarrow c$  is provided by the presence of a ‘near-by’ resonance with appropriate quantum numbers. If  $B_d$  decays are affected, so will be those of  $B_u$  and by the same amount, but not  $B_s$ .



Likewise a resonance near the  $B_s$  could affect its transitions, but not those of  $B_{u,d}$ . Nature had to be truly malicious to place one resonance next to  $B_{u,d}$  and a second one next to the  $B_s$ . Barring that a comparison of the values of  $|V(cb)|$  obtained from  $B$  and  $B_s$  decays would allow us to gauge QHdu violations in those transitions. The situation is more complex for  $b \rightarrow u$ , though, as already alluded to. An isoscalar or isovector resonance would affect  $B_u$  and  $B_d$  modes differently.

## 2.4 Lifetimes as Validation Studies

Among the many several important lessons to be derived from the lifetimes of charm and beauty hadrons I will emphasize just one aspect: with QHdu violations expected to be larger in nonleptonic than semileptonic decays, one can view studies of lifetimes as validation studies. The new measurements reported on  $D^0$ ,  $D^+$ ,  $D_s$  and  $\Lambda_c$  are in line with previous measurements and do not change the overall picture [28]: (i) The  $D^0$ - $D^+$  lifetime difference is given mainly by Pauli interference yielding a ratio of  $\sim 2 \cdot (f_D/200 \text{ MeV})^2$ . (ii) Weak annihilation should contribute in *mesons* on the 10 - 20 % level. (iii) The ratio  $\tau(D_s)/\tau(D^0)$  is fully consistent with such a semiquantitative picture. (iv) What is missing for a full evaluation are more accurate  $\Xi_c$  lifetimes: measurements of  $\tau(\Xi_c^{0,+})$  with 10 - 15 % accuracy are needed for this purpose.

The situation of beauty lifetimes has changed in one respect: the world average for the  $B^+$ - $B_d$  lifetime ratio now shows a significant excess over unity in agreement with a prediction using factorization:

$$\frac{\tau(B^-)}{\tau(B_d)} = 1.07 \pm 0.02 \text{ exp. [1] } \text{ vs. } 1 + 0.05 \cdot \left( \frac{f_B}{200 \text{ MeV}} \right)^2 \text{ theor. [28]} \quad (14)$$

The discrepancy for  $\tau(\Lambda_b)$  has remained basically the same:

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.794 \pm 0.053 \text{ exp. [1] } \text{ vs. } 0.88 - 1.0 \text{ theor. [28]} \quad (15)$$

While this could signal a significant limitation to QHdu, I like to reserve my judgement till CDF and D0 measure  $\tau(\Lambda_b)$  &  $\tau(\Xi_b^{0,-})$  in the next run.

The most striking success has been the apparently correct prediction of the  $B_c$  lifetime:  $\tau(B_c) \sim 0.5 \text{ psec}$  [29] vs. the CDF findings  $0.46 \pm 0.17 \text{ psec}$  with  $\tau(B_c)/\tau(B_d) \sim 1/3$ : the absence of a  $1/m_Q$  correction is essential here. The  $B_s$  lifetime deserves further dedicated scrutiny since theoretically one expects with confidence  $\tau(B_s)/\tau(B_d) = 1 \pm \mathcal{O}(0.01)$  vs. the experimental value of  $0.945 \pm 0.039$ .

## 2.5 Exclusive Nonleptonic $B$ Decays – another New Frontier

In describing nonleptonic two-body modes  $B \rightarrow M_1 M_2$  valuable guidance has been provided by symmetry considerations based on  $SU(2)$  and to a lesser degree  $SU(3)$ .

Phenomenological models have played an important role; more often than not they involve factorization as a central assumption. Such models still play an important role in widening our horizon when used with common sense [30]. Yet the bar has been raised for them by the emergence of a new theoretical framework for dealing with these decays. The essential pre-condition for this framework is the large energy release, and it invokes concepts like ‘colour transparency’ [31]; while those have been around for a while, only now they are put into a comprehensive framework. Two groups have presented results on this [32, 33]. The common feature in their approaches is that the decay amplitude is described by a kernel containing the ‘hard’ interaction given by a perturbatively evaluated effective Hamiltonian folded with form factors, decay constants and light-cone distributions into which the long distance effects are lumped; this *factorization* is symbolically denoted by

$$\langle M_1 M_2 | H | B \rangle = f_{B \rightarrow M_1} f_{M_2} T^H * \Phi_{M_2} + \dots \quad (16)$$

The two groups differ in their dealings with the soft part: BBNS regularize the divergent IR integrals they encounter at the price of introducing low energy parameters. KLS on the other hand invoke Sudakov form factors to shield them against IR singularities. It is not surprising that the two groups arrive at different conclusions: while BBNS infer final state interactions to be mostly small in  $B \rightarrow \pi\pi, K\pi$  with weak annihilation being suppressed, KLS argue for weak annihilation to be important with final state interactions *not* always small.

The trend of these results have certainly the ring of truth for me: e.g., while factorization represents the leading effect in most cases (including  $B \rightarrow D\pi$ ), it is not of universal quality. One should also note that the *non*-factorizable contributions move the predictions for branching ratios towards the data – a feature one could not count on *a priori*. It is not clear to me yet whether the two approaches are complementary or irreconcilable. Secondly one should view these predictions as preliminary: a clear disagreement with future data should be taken as an opportunity for learning rather than for discarding the whole approach. This is connected with a third point: there are corrections of order  $\Lambda/m_b$  which are beyond our computational powers. Since  $\Lambda$  might be as large as 0.5 - 1 GeV, they could be sizeable.

## 2.6 Radiative $B$ Decays

The transition  $B \rightarrow \gamma X$  has been the first correctly predicted penguin footprint. The CLEO number is still the most accurate one, but the BELLE result is not far behind

$$\text{BR}(B \rightarrow \gamma X_{no\ charm}) = (3.15 \pm 0.35 \pm 0.32 \pm 0.26) \cdot 10^{-4} \text{ CLEO} \quad (17)$$

$$\text{BR}(B \rightarrow \gamma X_{no\ charm}) = (3.34 \pm 0.5 \pm 0.35 \pm 0.28) \cdot 10^{-4} \text{ BELLE} \quad (18)$$

The SM prediction as summarized in an illuminating talk by Misiak reads [34]

$$\text{BR}(B \rightarrow \gamma X_{no\ charm})|_{\text{SM}} = (3.29 \pm 0.33) \cdot 10^{-4} \quad (19)$$

While the central value and the uncertainty have hardly changed over the last four years, an impressive theoretical machinery has been developed resulting in many new calculations – with the result that new contributions largely cancel. Careful analysis of the photon spectrum is under way, which is necessary to determine the branching ratio even more precisely and to determine the shape function needed to extract  $|V(ub)|$  from the lepton endpoint spectrum [43].

The results and caveats for  $B \rightarrow l^+l^-X$  have been updated. One should note that New Physics in general impacts  $B \rightarrow \gamma X$  and  $B \rightarrow l^+l^-X$  quite differently.

### 3 CP Violation in $\Delta S, \Delta B \neq 0$

The quantity  $\epsilon'/\epsilon$  describes the difference in CP violation between  $K_L \rightarrow \pi^+\pi^-$  and  $K_L \rightarrow \pi^0\pi^0$ :

$$\text{Re} \frac{\epsilon'}{\epsilon} = \frac{1}{6} \left[ \frac{\Gamma(K_L \rightarrow \pi^+\pi^-)/\Gamma(K_S \rightarrow \pi^+\pi^-)}{\Gamma(K_L \rightarrow \pi^0\pi^0)/\Gamma(K_S \rightarrow \pi^0\pi^0)} - 1 \right] \quad (20)$$

Within the KM ansatz direct CP violation has to exist, yet it is suppressed by the  $\Delta I = 1/2$  rule and the large top mass:  $0 < \epsilon'/\epsilon \ll 1/20$ . A guesstimate suggests  $\epsilon'/\epsilon \sim \mathcal{O}(10^{-3})$  [36]. The effective CP odd  $\Delta S = 1$  Lagrangian has been calculated with high accuracy on the quark level [35]; eight operators emerge. Evaluating their hadronic matrix elements with the available techniques one finds four positive and four negative contributions of roughly comparable size giving rise to large cancellations and thus enhanced uncertainties with central values typically below  $10^{-3}$ . While such studies found sizeable  $\Delta I = 1/2$  enhancements they fell well short of the observed size; various rationalizations were given for this failure, and overcoming it was left as a homework assignment for lattice QCD. However there were dissenting voices arguing for a more phenomenological approach where reproducing the  $\Delta I = 1/2$  rule is imposed as a goal. Not surprisingly this required the enhancement of some operators more than others thus reducing the aforementioned cancellations and increasing the prediction for  $\epsilon'/\epsilon$  [37]. The first KTeV data gave considerable respectability to this approach and lead to re-evaluations of other studies leading to somewhat larger predictions, as discussed at this conference [38].

This illustrates that theoretical uncertainties are very hard to estimate reliably, although in fairness two things should be pointed out: (i) Due to the large number on contributions with different signs one is facing an unusually complex situation. (ii) While there is no doubt that  $\epsilon' \neq 0$  holds, its exact size is still uncertain:

$$\text{Re} \left( \frac{\epsilon'}{\epsilon} \right) = (2.80 \pm 0.41) \cdot 10^{-3} \quad \text{KTeV}, (1.40 \pm 0.43) \cdot 10^{-3} \quad \text{NA48}; \quad (21)$$

some of the earlier theoretical expectations might experience some vindication still. In any case we are eagerly awaiting the new results from KTeV.

Our interpretation of the data is thus still in limbo: it might represent another striking success for the KM scheme with the  $\Delta I = 1/2$  rule explained in one fell

swoop – or it might be dominated by New Physics. I am not very confident that analytical methods can decide this issue, although some interesting new angles have been put forward on the  $\Delta S = 1/2$  rule [39]. One has to hope for lattice QCD to come through, yet it has to go beyond the quenched approximation, which will require more time.

Although CP violation implies T violation due to the CPT theorem, I consider it highly significant that more direct evidence has been obtained through the ‘Kabir test’: CPLEAR has found [40]

$$A_T \equiv \frac{\Gamma(K^0 \rightarrow \bar{K}^0) - \Gamma(\bar{K}^0 \rightarrow K^0)}{\Gamma(K^0 \rightarrow \bar{K}^0) + \Gamma(\bar{K}^0 \rightarrow K^0)} = (6.6 \pm 1.3 \pm 1.0) \cdot 10^{-3} \quad (22)$$

versus the value  $(6.54 \pm 0.24) \cdot 10^{-3}$  inferred from  $K_L \rightarrow \pi^+\pi^-$ . Of course, some assumptions still have to be made, namely that *semileptonic*  $K$  decays obey CPT or that the Bell-Steinberger relation is satisfied with *known* decay channels only. Avoiding both assumptions one can write down an admittedly contrived scheme where the CPLEAR data are reproduced *without* T violation; the price one pays is a large CPT asymmetry  $\sim \mathcal{O}(10^{-3})$  in  $K^\pm \rightarrow \pi^\pm\pi^0$  [42].

KTeV and NA48 have analyzed the rare decay  $K_L \rightarrow \pi^+\pi^-e^+e^-$  and found a large *T-odd* correlation between the  $\pi^+\pi^-$  and  $e^+e^-$  planes in full agreement with predictions [41]. Let me add just two comments here: (i) This agreement cannot be seen as a success for the KM ansatz. Any scheme reproducing  $\eta_{+-}$  will do the same. (ii) The argument that strong final state interactions (which are needed to generate a T odd correlation above 1% with T invariant dynamics) cannot affect the relative orientation of the  $e^+e^-$  and  $\pi^+\pi^-$  planes fails on the quantum level [42].

One often hears that observing a CP asymmetry in  $B \rightarrow \psi K_S$  is no big deal since it is confidently expected – unless it clearly falls outside the predicted range – and likewise in  $B \rightarrow \pi^+\pi^-$  since it cannot be interpreted cleanly due to Penguin ‘pollution’ and the value of its asymmetry is hardly constrained. Such sentiments, however, miss the paradigmatic character of such observations: (a) An asymmetry in  $B \rightarrow \psi K_S$  would be the first one observed outside  $K_L$  decays, it would have to be big to be established in the near future and it would establish the KM ansatz as a major agent. (b) Likewise an asymmetry in  $B \rightarrow \pi^+\pi^-$  again would have to be big, and it would probably reveal *direct* CP violation to be big as well in beauty decays.

These CP asymmetries are described in terms of the angles of the usual unitarity triangle. An ecumenical message in PDG2000 endorses two different notations, namely

$$\phi_1 \equiv \beta = \pi - \arg\left(\frac{V_{tb}^*V_{td}}{V_{cb}^*V_{cd}}\right), \phi_2 \equiv \alpha = \arg\left(\frac{V_{tb}^*V_{td}}{-V_{ub}^*V_{ud}}\right), \phi_3 \equiv \gamma = \arg\left(\frac{V_{ub}^*V_{ud}}{-V_{cb}^*V_{cd}}\right). \quad (23)$$

From CP insensitive rates one can deduce the sides of this triangle and from CP asymmetries the angles: e.g., from  $\epsilon/\Delta m(B_d)$  one can infer  $\sin 2\phi_1$ . A whole new industry has sprung up for doing these fits. Typical examples are (I will discuss

caveats below):

$$\sin 2\phi_1 = 0.716 \pm 0.070 [2] \leftrightarrow 0.7 \pm 0.1 [44] \quad (24)$$

$$\sin 2\phi_2 = -0.26 \pm 0.28 [2] \leftrightarrow -0.25 \pm 0.6 [44] \quad (25)$$

The first results from the asymmetric  $B$  factories leave us in limbo:

$$\sin 2\phi_1 = 0.45^{+0.43+0.07}_{-0.44-0.09} \text{ BELLE} \quad (26)$$

$$\sin 2\beta = 0.12 \pm 0.37 \pm 0.09 \text{ BaBar} \quad (27)$$

Nevertheless one can raise the question what we would learn from a ‘Michelson-Morley outcome’, if, say,  $|\sin 2\phi_1| < 0.1$  were established? Firstly, we would know that the KM ansatz would be ruled out as a major player in  $K_L \rightarrow \pi\pi$  – there would be no plausible deniability! Secondly, one would have to raise the basic question why the CKM phase is so suppressed, unless there is a finely tuned cancellation between KM and New Physics forces in  $B \rightarrow \psi K_S$ ; this would shift then the CP asymmetry in  $B \rightarrow \pi\pi, \pi\rho$ .

## 4 Probing for New Physics

$\Delta S = 1, 2$  dynamics have provided several examples of revealing the intervention of features that represented New Physics *at that time*; it thus has been instrumental in the evolution of the SM. This happened through the observation of ‘qualitative’ discrepancies; i.e., rates that were expected to vanish did not, or rates were found to be smaller than expected by several orders of magnitude. Such an indirect search for New Physics can be characterised as a ‘King Kong’ scenario: one might be unlikely to encounter King Kong; yet once it happens there can be no doubt that one has come across something out of the ordinary. Such a situation can be realized for charm and  $K_{\mu 3}$  decays and EDMs.

### 4.1 $D^0$ Oscillations & CP Violation

It is often stated that  $D^0$  oscillations are slow and CP asymmetries tiny within the SM and that therefore their analysis provides us with zero-background searches for New Physics.

Oscillations are described by the normalized mass and width differences:  $x_D \equiv \frac{\Delta M_D}{\Gamma_D}$ ,  $y_D \equiv \frac{\Delta \Gamma}{2\Gamma_D}$ . A conservative SM estimate yields  $x_D, y_D \sim \mathcal{O}(0.01)$ . Stronger bounds have appeared in the literature, namely that the OPE contributions are completely insignificant and that long distance contributions *beyond* the OPE provide the dominant effects yielding  $x_D^{SM}, y_D^{SM} \sim \mathcal{O}(10^{-4} - 10^{-3})$ . A recent detailed analysis [45] revealed that a proper OPE treatment reproduces also such long distance contributions with

$$x_D^{SM}|_{OPE}, y_D^{SM}|_{OPE} \sim \mathcal{O}(10^{-3}) \quad (28)$$

and that  $\Delta\Gamma$ , which is generated from on-shell contributions, is – in contrast to  $\Delta m_D$  – insensitive to New Physics while on the other hand more susceptible to violations of QHDu.

Four experiments have reported new data on  $y_D$  [1]:

$$y_D = (0.8 \pm 2.9 \pm 1.0)\% \text{ E791} \quad , \quad (3.42 \pm 1.39 \pm 0.74)\% \text{ FOCUS} \quad (29)$$

$$y_D = (1.0^{+3.8+1.1}_{-3.5-2.1})\% \text{ BELLE} \quad , \quad y'_D = (-2.5^{+1.4}_{-1.6} \pm 0.3)\% \text{ CLEO} \quad (30)$$

E 791 and FOCUS compare the lifetimes for two different channels, whereas CLEO fits a general lifetime evolution to  $D^0(t) \rightarrow K^+\pi^-$ ; its  $y'_D$  depends on the strong rescattering phase between  $D^0 \rightarrow K^-\pi^+$  and  $D^0 \rightarrow K^+\pi^-$  and therefore could differ substantially from  $y_D$  – even in sign [46] – if that phase were sufficiently large. The FOCUS data contain a suggestion that the lifetime difference in the  $D^0 - \bar{D}^0$  complex might be as large as  $\mathcal{O}(1\%)$ . If  $y_D$  indeed were  $\sim 0.01$ , two scenarios could arise for the mass difference. If  $x_D \leq \text{few} \times 10^{-3}$  were found, one would infer that the  $1/m_c$  expansion yields a correct semiquantitative result while blaming the large value for  $y_D$  on a sizeable and not totally surprising violation of QHDu. If on the other hand  $x_D \sim 0.01$  would emerge, we would face a theoretical conundrum: an interpretation ascribing this to New Physics would hardly be convincing since  $x_D \sim y_D$ . A more sober interpretation would be to blame it on QHDu violation or on the  $1/m_c$  expansion being numerically unreliable. Observing  $D^0$  oscillations then would not constitute a ‘King Kong’ scenario.

Searching for *direct* CP violation in Cabibbo suppressed  $D$  decays as a sign for New Physics would also represent a very complex challenge: within the KM description one expects to find some asymmetries of order 0.1 %; yet it would be hard to conclusively rule out some more or less accidental enhancement due to a resonance etc. raising an asymmetry to the 1% level.

The only clean environment is provided by CP violation involving  $D^0$  oscillations, like in  $D^0(t) \rightarrow K^+K^-$  and/or  $D^0(t) \rightarrow K^+\pi^-$ . For the asymmetry would depend on the product  $\sin(\Delta m_D t) \cdot \text{Im}[T(\bar{D} \rightarrow f)/T(D \rightarrow \bar{f})]$ : with both factors being  $\sim \mathcal{O}(10^{-3})$  in the SM one predicts a practically zero effect.

## 4.2 $P_\perp(\mu)$ in $K^+ \rightarrow \mu^+\pi^0\nu$

The muon polarization transverse to the decay plane in  $K^+ \rightarrow \mu^+\pi^0\nu$  represents a T-odd correlation  $P_\perp(\mu) = \langle \vec{s}(\mu) \cdot (\vec{p}(\mu) \times \vec{p}(\pi)) / |\vec{p}(\mu) \times \vec{p}(\pi)| \rangle$ , which in this case could not be faked realistically by final-state interactions and would reveal genuine T violation. With  $P_\perp(\mu) \sim 10^{-6}$  in the SM, it would also reveal New Physics that has to involve chirality breaking weak couplings:  $P_\perp(\mu) \propto \text{Im}\xi$ , where  $\xi \equiv f_-/f_+$  with  $f_-$  [ $f_+$ ] denoting the chirality violating [conserving] decay amplitude. There are ‘ancient’ data yielding

$$\text{Im}\xi = -0.01 \pm 0.019 \leftrightarrow P_\perp(\mu) = (-1.85 \pm 3.6) \cdot 10^{-3} \quad (31)$$

A new preliminary result from the ongoing experiment was reported here:

$$\text{Im}\xi = -0.013 \pm 0.016 \pm 0.003 . \quad (32)$$

### 4.3 EDM's

Electric dipole moments  $d$  of non-degenerate systems represent direct evidence for T violation. The present bounds read:

$$d_{neutron} < 9.7 \cdot 10^{-26} \text{ ecm} \quad (33)$$

$$d_{electron} = (-0.3 \pm 0.8) \cdot 10^{-26} \text{ ecm} \quad (34)$$

With the KM scheme predicting unobservably tiny effects (with the only exception being the ‘strong CP’ problem), and many New Physics scenarios yielding  $d_{neutron}, d_{electron} \geq 10^{-27} \text{ ecm}$ , this is truly a promising zero background search for New Physics!

### 4.4 KM Trigonometry

There certainly exists the potential for a ‘qualitative’ discrepancy in the CP asymmetries for  $B$  decays. The cleanest case is given by the CP asymmetry in  $B_s(t) \rightarrow \psi\eta$  or  $B_s(t) \rightarrow \psi\phi$ , which is Cabibbo suppressed [47] and thus below 4% due to three-family unitarity.

Yet otherwise the situation in  $\Delta B = 1, 2$  is more complex meaning it provides more opportunities, yet also more challenges. For one will be looking for *quantitative* discrepancies between predictions and the data that *cannot* amount to orders of magnitude.

With three families there are actually six unitarity triangles. They contain three types of angles:

1. Angles of order unity like  $\phi_{1,2,3}$ ; they differ from each other in order  $\lambda^2$ .
2. Angles that themselves are of order  $\lambda^2$ ; the most accessible representative is an angle in the  $bs$  triangle often referred to as  $\chi$ :

$$\chi = \phi_1^{bs} = \pi + \arg\left(\frac{V_{cs}^* V_{cb}}{V_{ts}^* V_{tb}}\right) \simeq \lambda^2 \eta \quad (35)$$

which controls the aforementioned asymmetry in  $B_s(t) \rightarrow \psi\phi, \psi\eta$  [47].

3. Angles  $\sim \mathcal{O}(\lambda^4)$ , the least inaccessible one being in the  $cu$  triangle often referred to as  $\chi'$

$$\chi' = \phi_3^{cu} = \arg\left(\frac{-V_{ud}^* V_{cd}}{V_{us}^* V_{cs}}\right) \simeq -\lambda^4 A^2 \eta ; \quad (36)$$

it controls CP asymmetries in  $D$  decays [48].

A comprehensive program will have to undertake three steps:

- measure the large angles  $\phi_{1,2,3}$  (and their ‘cousins’) and check their correlations with the sides of the triangle;
- check whether the small [tiny] angle  $\chi$  [ $\chi'$ ] is indeed small [tiny];
- attempt to measure the  $\mathcal{O}(\lambda^2)$  differences between  $\phi_{1,2,3}$  and their cousins.

All of these represent searches for New Physics with in particular the last item probing features of such New Physics beyond its ‘mere’ existence.

With many of the SM effects being large or at least sizeable, one is looking for deviations from expectations that are mostly of order unity. A typical scenario would be that an asymmetry of, say, 40 % is expected, yet 80% is observed; how confident could we be in claiming New Physics? What about 40% vs. 60% or even 50%? The situation is thus qualitatively different from  $K$  decays where *original* expectations and data differed by orders of magnitude! Therefore we have to be very conscious of three scourges: (i) Systematic experimental uncertainties; (ii) experiments could be wrong – an issue addressed by the ‘combiner’ program [44]; (iii) theoretical uncertainties!

## 4.5 On Theoretical Uncertainties

While considerable experience and awareness exists concerning the *quantitative* aspects of experimental shortcomings, this is not so with respect to theoretical uncertainties. My understanding behind quoting the latter is the following: ”I would be very surprised if the true value would fall outside the stated range.” Such a statement is obviously hard to quantify.

An extensive literature on how to evaluate them has emerged over the last two years in particular (see, for example, [2, 44]). It seems to me that the passion of the debate has overshadowed the fact that a lot of learning has happened. For example it is increasingly understood that any value within a stated range has to be viewed as equally likely. While concerns are legitimate that some actors might be overly aggressive in stating constraints on the KM triangle, it would be unfair to characterize them as silly. I also view it as counterproductive to bless one approach while anathematizing all others ‘ex cathedra’. I believe many different paths should be pursued since ”good decisions come from experience that often is learnt from bad decisions”.

Our most powerful weapon for controlling theoretical uncertainties will again be *overdetermining* basic quantities by extracting their values from more than one independent measurement. In this respect the situation is actually more favourable in  $B$  than in  $K$  decays since there are fewer free parameters *relative* to the number of available decay modes. Once the investment has been made to collect the huge number of decays required to obtain a sufficient number of the transitions of primary interest – say  $B_d \rightarrow \psi K_S \rightarrow (l^+ l^-)_\psi (\pi^+ \pi^-)_{K_S}$  – then we have also a slew of many



other channels that can act as cross checks or provide us with information about hadronization effects etc. Finally one should clearly distinguish the goal one has in mind: does one want to state the most likely expectation – or does one want to infer the presence of New Physics from a discrepancy between expectations and data? The latter goal is of course much more ambitious where for once being conservative is a virtue!

## 4.6 Looking into the Crystal Ball

I expect various large CP asymmetries to be found in  $B$  decays – including direct CP violation – over the next 15 years that agree with the KM expectations to first order, yet exhibit smallish, though definite deviations thus revealing the intervention of New Physics. However it is conceivable that the whole future beauty phenomenology can be accommodated in the CKM ansatz. Would that mean our efforts will have been wasted?

My answer is an emphatic no! The pattern in the Yukawa couplings often referred to as ‘textures’ is presumably determined by very high scale dynamics. They provide the seeds for the quark mass matrix arising when Higgs fields develop vacuum expectation values at much lower scales. The quark mass matrix yields the quark masses and the CKM angles and phase. My conjecture is that such textures follow a simple pattern yielding ‘special’ CKM parameters. From the observed values of CKM quantities one can thus infer information on the dynamics at very high scales.

Yet what is a manifestly simple pattern at very high energies will look quite different at the electroweak scales that can be probed: renormalization will tend to wash out striking features. This again calls for *precise* extractions of these fundamental parameters.

## 5 Conclusions & Outlook

We have reached an exciting and even decisive phase in flavour dynamics.

- Since the phenomenological success of the CKM description is a priori quite surprising, it must contain a deep, albeit hidden message.
- New (sub)paradigms have been established or are about to be established: direct CP violation has been found, intriguing hints for the first CP asymmetry outside  $K_L$  decays have emerged and the CKM predictions for CP violation in  $B$  decays are about to be tested. These represent *high sensitivity* probes of dynamics and contain many possible portals to New Physics.
- Basic quantities have become known with good accuracy and the promise for even more: the beauty quark mass is known to within about 1.5 % – the most precise quark mass; the top mass is known to within 3% [10 %] due to direct

observation [radiative corrections];  $|V_{cb}|$  has been extracted with about 5 % or so accuracy with a reduction down to  $\sim 2$  % appearing feasible; the error on  $|V_{ub}|$  of presently about 40 % should be reduced to the 10% level with 5% not appearing to be impossible in the long run; for  $|V_{td}|$  with its present uncertainty  $\sim 60$  % a reduction down to 10 % again might not be impossible. Thus  $B$  physics will develop into a *high precision* probe for New Pghysics as well.

- These developments have been made possible by *practical* theoretical technologies having been greatly improved: there has been increasing sophistication in treating semileptonic and radiative  $B$  decays; a new frontier has emerged in treating exclusive nonleptonic  $B$  decays with intriguing classification schemes truly based on QCD that might allow us to calculate these transitions in the real world.
- Theoretical uncertainties constitute mostly systematic uncertainties with hidden correlations. They can reliably be evaluated only through overconstraints. Prior to that they should be considered *preliminary*; in that context I would like to appeal to the community to accord us theorists the same professional courtesies that is granted to experimental analyses.
- To make good use of such developments we need experimental programs that allow *precise* measurements in a *comprehensive* way rather than just one or two precise ones. It will be an exciting adventure to find out how far such a program can be pushed. In this context I applaud the managements of CERN and FNAL for their wisdom in approving LHC-b and BTeV.
- There are other areas that might well contain portals to New Physics: dedicated searches for CP violation in charm decays, EDMs and transverse muon polarization in  $K_{\mu 3}$  decays are an absolute must since any improvement in experimental sensitivity might reveal an effect. This is even more so in light of recent efforts to explain baryogenesis as being driven by leptogenesis in the Universe.
- We have heard of mounting evidence for neutrino oscillations, which require neutrino masses to be nondegenerate implying lepton flavour eigenstates to differ from lepton mass eigenstates; the saw-see mechanism provides an attractive framework for explaining the smallness of neutrino masses. There are intriguing connections between the atmospheric neutrino anomaly and  $\tau \rightarrow \mu \gamma$  and between the solar neutrino anomaly and  $\mu \rightarrow e \gamma$  in the context of SUSY GUTs [49].

In future meeting there will be detailed discussions of the lepton analogue to the Cabibbo-Kobayashi-Maskawa matrix, the Maki-Nakagawa-Sakata [50] matrix indicating that leptons after all are ‘exactly like quarks – only different!’.

## Acknowledgements

The organizers deserve thanks for their smooth organization of this conference in the lively city of Osaka. I have benefitted from discussions with A. Golutvin, M. Beneke and A. Sanda. This work has been supported by the NSF under the grant PHY 96-05080.

## References

- [1] A. Golutvin, these Proc.
- [2] see, for example: A. Stocchi, these Proc.
- [3] R. Kenway, these Proc.
- [4] I. Bigi, Y. Dokshitzer, V. Khoze, J. Kühn, P. Zerwas, *Phys. Lett.* **B 181** (1986) 157.
- [5] M. Voloshin, *Int. J. Mod. Phys.* **A10** (1995) 2865.
- [6] K. Melnikov, A. Yelkhovsky, *Phys. Rev.* **D 59** (1999) 114009.
- [7] A. Hoang, *Phys. Rev.* **D 61** (2000) 034005.
- [8] M. Beneke and A. Signer, *Phys. Lett.* **B 471** (1999) 233.
- [9] A. Falk, M. Luke, M. Savage, *Phys. Rev.* **D 53** (1996) 2491.
- [10] A. Kronfeld, J. Simone, hep-ph/0006345.
- [11] I.I. Bigi, M.Shifman, N. Uraltsev, A. Vainshtein, *Phys. Rev.* **D 52** (1995) 196.
- [12] I.I. Bigi, M.Shifman, N. Uraltsev, *Annu. Rev. Nucl. Part. Sci.* **47** (1997) 591, with references to earlier work.
- [13] I. Bigi, hep-ph/9907270.
- [14] The BABAR Physics Book, P. Harrison & H. Quinn (eds.), SLAC-R-504.
- [15] J. Simone et al., *Nucl. Phys. Proc. Supp.* **83** (2000) 334.
- [16] K. Ecklund, these Proc.
- [17] E. Barberio, these Proc.
- [18] I.I. Bigi, M.Shifman, N. Uraltsev, A. Vainshtein, *Phys. Lett.* **B 328** (1994) 431.
- [19] N. Uraltsev, *Int. J. Mod. Phys.* **A14** (1999) 4641.
- [20] V. Barger, C.S. Kim, G. Phillips, *Phys. Lett.* **B 251** (1990) 629.

- [21] R. Dikeman, N. Uraltsev, *Nucl. Phys.* **B 509** (1998) 378; I. Bigi, R. Dikeman, N. Uraltsev, *Eur. Phys. J.* **C4** (1998) 453.
- [22] A. Falk, Z. Ligeti, M. Wise, *Phys. Lett.* **B 406** (1997) 255.
- [23] C. Bauer, Z. Ligeti, M. Luke, hep-ph/0002161.
- [24] G. Buchalla, A. Buras, *Nucl. Phys.* **B 548** (1999) 309.
- [25] B. Grinstein, R. Lebed, *Phys. Rev.* **D 57** (1998) 1366; *ibidem* **D 59** (1999) 054022.
- [26] I.I. Bigi, M. Shifman, N. Uraltsev, A. Vainshtein, *Phys. Rev.* **D 59** (1999) 054011; I.I. Bigi, N. Uraltsev, *Phys. Rev.* **D 60** (1999) 114034; I.I. Bigi, N. Uraltsev, *Phys. Lett.* **B 457** (1999) 163.
- [27] R. Lebed, N. Uraltsev, hep-ph/0006346.
- [28] G. Bellini, I. Bigi, P. Dornan, *Phys. Rep* **289** (1997) 1.
- [29] I. Bigi, *Nucl. Instr. & Meth. in Phys. Res.* **A 351** (1994) 240; *Phys. Lett.* **B 371** (1996) 105; M. Beneke, G. Buchalla, *Phys. Rev.* **D 53** (1996) 4991.
- [30] See the contrib. by R. Fleischer, H.-Y. Cheng, G. Hou, these Proc.
- [31] See, e.g., B. Ward, *Phys. Rev.* **D 51** (1995) 6253.
- [32] M. Beneke, G. Buchalla, M. Neubert, C. Sachrajda, hep-ph/0007256.
- [33] Y.-Y. Keum, H.-n. Li, A. Sanda, hep-ph/0004173.
- [34] M. Misiak, these Proc.
- [35] A. Buras, P. Gambino, M. Gorbahn, S. Jager, L. Silvestrini, hep-ph/0007313.
- [36] M. Fabbrichesi, these Proc.
- [37] S. Bertolini, J. Eeg, M. Fabbrichesi, *Rev. Mod. Phys.* **72** (2000) 65.
- [38] See the contrib. by H.-Y. Cheng, G. Golowich, J. Prades, G. Valencia, these Proc.
- [39] J. Prades, *Nucl. Phys. B (Proc. Suppl.)* **86** (2000) 294.
- [40] A. Apostolakis et al., *Phys. Lett.* **B 444** (1998) 43; *Phys. Lett.* **B 456** (1999) 297.
- [41] L. Sehgal, M. Wanninger, *Phys. Rev.* **D 46** (1992) 1035; 5209 (E).
- [42] I. Bigi, A. Sanda, *Phys. Lett.* **B 466** (1999) 33.

- [43] M. Neubert, *Phys. Rev. D* **49**(1994) 4623; I.I. Bigi, M.Shifman, N. Uraltsev, A. Vainshtein, *Int. J. Mod. Phys. A* **9** (1994) 2467.
- [44] A. Hoecker, H. Lacker, S. Laplace, F. Le Diberder, preliminary results obtained using a non-Bayesian approach, paper in preparation.
- [45] I. Bigi, N. Uraltsev, hep-ph/0005089.
- [46] S. Bergmann, Y. Grossman, Z. Ligeti, Y. Nir, A. Petrov, *Phys. Lett. B* **486** (2000) 418.
- [47] I. Bigi, A.I. Sanda, *Nucl. Phys. B* **193** (1981) 85.
- [48] I.I. Bigi, in: Proc. of the Tau-Charm Factory Workshop, 1989, SLAC-Report-343.
- [49] S. Baek, T. Goto, Y. Okada, K.-I. Okumura, hep-ph/0002141.
- [50] Z. Maki, M. Nakagawa, S. Sakata, *Prog. Theor. Phys.* **30** (1963) 727.